JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D20205, doi:10.1029/2006JD007820, 2007

Evolution of lightning in an isolated hailstorm of moderate size in the tropics

A. K. Kamra[1] and S. D. Pawar[1]

Received 24 July 2006; revised 12 March 2007; accepted 13 July 2007; published 20 October 2007.

[1] Evolution of lightning activity in a tropical hailstorm of moderate size that developed in the premonsoon season at Pune (18°32′N, 73°51′E, 559 m above sea level) is studied from the measurements of surface electric field, the Maxwell current and thunder. Total flash rate is counted from the electric field record, and the cloud-to-ground (CG) flash rate is estimated from the visual observations. Precise timings of their occurrence were confirmed from the observations of overshoot in the Maxwell current records. The storm exhibited an almost constant rate of one CG flash every 1 to 2 min over the whole life time of the storm. The ratio of intracloud (IC) to CG flashes (IC/CG) increased with the increase in total flash rate. In the convective stage of the storm, field changes from consecutive flashes were generally found to alternate in polarity. Moreover, in this stage, field changes occur in pairs, the first field change of each pair being of negative polarity and the second one of positive polarity. The two field changes in a pair occur with an average time difference of 14.3 ± 8.4 s while two consecutive pairs appear after 29.3 ± 9.1 s. In between the convective and mature stages, our observations suggest the occurrence of the phenomenon of rain gush and the field excursion associated with falling precipitation. Development of the mature stage was marked with rapid transitions in the surface electric field and the Maxwell current polarities from negative to positive. Further, total flash rate and IC/CG ratio sharply increase, and the lightning-induced electric field changes become almost exclusively of negative polarity. Observations suggest possibly a lifting up of the charging region in mature stage of the storm. The dissipating stage of the storm witnessed hail and rain showers, sharp transition of electric field and the Maxwell current from positive to negative polarity and occurrence of a few positive CG discharges. Our observations are consistent with the general belief that that some lightning flashes, by neutralizing and depositing charge in the region of opposite polarity, change the charge distribution so as to trigger another discharge in the storm.

Citation: Kamra, A. K., and S. D. Pawar (2007), Evolution of lightning in an isolated hailstorm of moderate size in the tropics, *J. Geophys. Res.*, *112*, D20205, doi:10.1029/2006JD007820.

1. Introduction

[2] In the air mass thunderstorms developing in barotropic environments of the tropics the updraft and thus the growth of the storm is nearly vertical and the accumulated condensate in the upper regions of storm frequently descends in place to create the low-level downdraft. A simplified picture of charge distribution in such thunderstorms can be represented by an electric dipole with the positive charge in the upper parts and the negative charge in the lower parts of the storm [*Wilson*, 1929]. Several airborne measurements made with balloons and aircraft, show that another region of positive charge also exists in cloud bases [*Simpson and Scrase*, 1937; *Simpson and Robinson*, 1941; *MacCready and Proudfit*, 1965; *Holden et al.*, 1983; *Marshall and Winn*, 1982; *Marshall and Stolzenburg*, 1998; *Bateman et al.*, 1999; *Mo et al.*, 2002]. This region is generally called the lower positive charge center (LPCC). Summarizing the past investigations, *Williams* [1989] concludes that several earlier measurements tend to confirm the tripole structure with different emphasis given to the LPCC and that an electrical tripole is a more accurate representation of thundercloud structure. However, *Marshall and Rust* [1991], *Rust and Marshall* [1996] and *Stolzenburg et al.* [1998] infer from the vertical profiles of electric field obtained from balloon-borne soundings through storms that the electrical structure of thunderstorms may be more complex than a simple dipole or tripole. Recent three-dimensional lightning-mapping observations of *Coleman et al.* [2003] which show that lightning can deposit charge of one polarity in localized regions of charge of opposite polarity, can help reconcile these observations of the complex and simpler charge structures. Recent investigations of *Warner et al.* [2003] and *Rust et al.* [2005] with an instrumented aircraft and ground-based three-dimensional lightning mapping array also confirm deposition of charge

[1]Indian Institute of Tropical Meteorology, Pune, India.

0148-0227/07/2006JD007820

by lightning flashes. Measurements of *Pawar and Kamra* [2002, 2004], and theoretical modeling of *Mansell et al.* [2002], point out to the emerging consensus that LPCC plays an important role in triggering lightning flashes and biasing CGs to ground.

[3] Development of electrification is closely related to the development of the dynamical and microphysical properties in the thundercloud [*Vonnegut*, 1963; *Krehbiel*, 1986; *Williams*, 2001]. In the most widely accepted of the thunderstorm charging mechanisms, interactions between graupel and ice crystals in presence of supercooled water result into charging of graupels with negative charge and ice crystals with positive charge when the graupels are growing by sublimation. The subsequent differential separation of particles under gravity is then assumed to cause creation of positive dipole. Results of the laboratory experiments of *Reynolds et al.* [1957], *Takahashi* [1978], and *Saunders et al.* [1991] suggest that the same charge separation mechanism can charge the graupel positively and create LPCC in tripole electrical structure when the graupel is undergoing deposition [*Williams*, 1989; *Williams et al.*, 1991; *Murphy et al.*, 1996]. *Mansell et al.* [2005] propose that inductive charging of particles in the lower part of cloud under the influence of overhead charge may be responsible for the LPCC. Observations of *Holden et al.* [1983], *Marshall and Winn* [1982], *Mo et al.* [2002], *Coleman et al.* [2003], *Warner et al.* [2003], and *Rust et al.* [2005] suggest that some flashes may deposit positive charge in the base of a thundercloud and thus act to generate the Lower Positive Charge Center (LPCC). From the dynamical aspect, the cumulus phase of a typical storm is characterized by a weak updraft and has accumulation of negative charge overhead as indicated by the positive electric field at the ground. In mature stage, updraft intensifies, and the surface electric field often changes polarity and is marked with frequent rapid transitions due to lightning. The dissipating stage is characterized by downdraft. Electric field at the ground mostly changes to negative polarity indicating positive charge overhead. The dissipating stage is generally marked by a few CG discharges of positive polarity [*Moore and Vonnegut*, 1977; *Marshall and Winn*, 1982; *Mo et al.*, 2002]. Interactions of dynamics, microphysics and electrification in thunderstorms are also demonstrated by the phenomena of rain gush [*Moore et al.*, 1964; *Szymanski et al.*, 1980], field excursion associated with precipitation (FEAWP) and the end-of-storm oscillation (EOSO) [*Moore and Vonnegut*, 1977; *Williams and Boccippio*, 1993].

[4] The presence of ice crystals and graupel is considered as fundamental for strong electrification and lightning [*Latham*, 1981; *Illingworth*, 1985; *Krehbiel*, 1986; *Williams*, 1989; *Saunders*, 1995]. However, studies of *Lang et al.* [2000] and *Soula et al.* [2004], show a decrease in the CG lightning activity with the appearance of hail in convective storms.

[5] Electrical processes operating inside thunderstorms generate large currents and the charges deposited by them considerably influence the Maxwell currents flowing outside the cloud. Therefore the Maxwell current flowing beneath a thunderstorm has often been interpreted to reflect the electrical processes occurring inside thunderstorms [*Krider and Musser*, 1982; *Krider and Blakeslee*, 1985]. For example, *Krider and Musser* [1982] equate the Maxwell currents to the charging currents in thunderstorms under conditions of low electric field, no precipitation and no lightning currents.

[6] *Moore and Vonnegut* [1977] and *Livingston and Krider* [1978] have analyzed the surface electric field to study the electrical state of the storm. In early years, from the electric field measurements made with a double-nozzle water dropper and an ionium collector below several thunderstorms during their passage over Bombay (now Mumbai) in the postmonsoon and premonsoon seasons, *Banerjee* [1930, 1932] reported that front part of the storms is negatively charged, the central part is positively charged and again, the rear part is negatively charged. In order to learn more of how the thunderstorms behave electrically in this region, we report our observations here. Recently, *Pawar and Kamra* [2002, 2004] have used their measurements of surface electric field and the Maxwell current to study the evolution of lightning and characteristics of lightning flashes in storms. They show that corona charge in subcloud layer modifies the shape of recovery curves of electric field and the charge deposited by an IC/CG discharge in region of opposite charge in the cloud can trigger another IC/CG discharge in the cloud. In this paper, we present our measurements of the surface electric field, the Maxwell current and thunder made below a tropical air mass hailstorm of moderate size. We use these observations to study the changing character of the lightning-induced electric field changes and to understand the role of lightning flashes in causing the redistribution of charge in the storm assuming the storm to be a tripole.

2. Instrumentation

[7] Observations have been made in Atmospheric Electricity Observatory at Pune (18°32′N, 73°51′E, 589 m above sea level) with the instruments described by *Pawar and Kamra* [2002, 2004], Atmospheric electric field is measured with a field mill with its sensor plates kept flush with the ground. Field mill consists of two stators which are periodically exposed to and shielded from the atmospheric electric field with a rotor fixed on the shaft of an a. c. synchronous motor of 1400 rpm and 12 W power. The diameter of rotor is 12 cm and it is made of nonmagnetic stainless steel. The rotor is grounded using a mercury cup at the other end of motor. Two stators are also made of the same material and of same diameter as the rotor. The stators are separated from each other by a distance of 0.5 cm with Teflon bushes. The stators are connected to the inverting inputs of two operational amplifiers (IC 8007). The magnitude of the charge induced on the stators is directly proportional to the intensity of the atmospheric electric field. The two amplified signals are 180° out of phase with each other. These two signals, after amplification, are fed to a demodulator (IC 1456) for combination into a single wave. The reference signal for the demodulator is generated with a circular plate with sectors cut of the same shape as that of rotor and fixed at the other end of motor. This circular plate rotates through an opto-separater and generates a square wave signal of same frequency as that of input signals and exactly in phase with one of the two input signals. Neglecting charge separation on splashing, nontransient rain current, as seen by the field mill would depend on the plate area exposed. Since the rotor

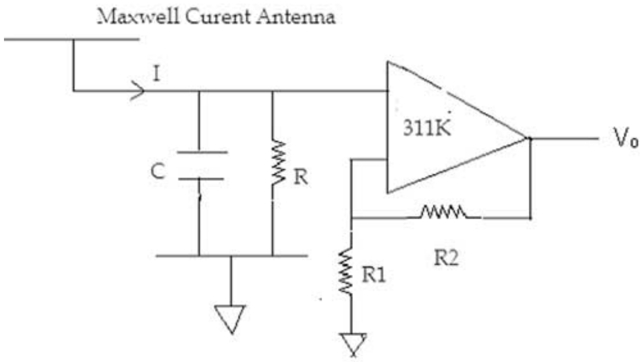

Figure 1. Circuit diagram of the amplifier used in the Maxwell current sensor.

has constant angular velocity, it would result in the out-of-phase triangular voltages at the two current amplifier outputs. The differential action of the demodulator would then give the signal with zero d. c. level. It can measure electric field of ±12.5 kV m^{-1} with response time of 0.1 s. Normally, it can sense the lightning-induced electrostatic field changes of an average thunderstorm 20–25 km away from the observatory.

[8] The Maxwell current is measured with a direct current measurement method using a slow antenna. The sensor consists of a 1 m^2 flat aluminum plate, also kept flush with the ground, on four porcelain insulators [*Deaver and Krider*, 1991]. The plate is connected to an electrometer with a resistor of 1000 MΩ in parallel with a 100 pF capacitor. With this arrangement, this instrument is able to measure the Maxwell current density of up to ±5 nA/m^2 with a decay time of 0.1 s. The decay time of 0.1 s is chosen so as to bypass the electric field changes produced by intrastroke processes [*Deaver and Krider*, 1991]. The electrometer used here is AD311K, a varactor bridge operational amplifier with very low bias current of the order of 10^{-14} A, low voltage drift 10 μV/°C and very high input impedance of the order of 10^{14} Ω. Figure 1 shows the circuit diagram of the amplifier used in the Maxwell current sensor.

[9] The Maxwell current sensor plate is mounted in a pit and its input is fed through a 30 cm long carbon-coated coaxial cable to an amplifier also placed in the pit. The output of amplifier is fed through an independent coaxial cable to a data -logger placed inside a hut 50 m away from the sensor.

[10] Since the displacement currents dominantly contribute to the Maxwell current, in matured stage of the storm, its detection range for lightning discharges in thunderstorms may exceed 50 km [*Deaver and Krider*, 1991]. During some periods when the Maxwell current is high and its signal has saturated the scale, its value has been estimated near the points of electric field reversal from a method based on its calculation from dE/dt. In this method, the rate of change of electric field, dE/dt, is calculated from the electric field recovery curves when the electric field is nearly zero and there is no precipitation [*Krider and Musser*, 1982] Under such conditions, the Maxwell current mostly consists of displacement current.

[11] We take the downward (upward) directed electric field as negative (positive). Accordingly, the conduction current bringing positive charge to the ground is taken as negative. The thunder is recorded with a microphone (AHUJA make) of the dynamic condenser type having impedance of 200 ohms, a sensitivity of 2.5 mV Pa^{-1} at 1 kHz and a flat frequency response from 20 to 20,000 Hz.

[12] A LM387 IC of National Semiconductor is used as the audio preamplifier. The LM387 is a dual preamplifier used to amplify low-level signals with optimum noise performance. It operates from single supply across the range of 9V to 30V. The amplifiers are internally compensated for gains greater than 10.

[13] The preamplifier circuit is designed to have gain up to 1000. To pickup very weak signals, another stage using LM741 IC (op-amp) is designed to increase the gain up to one order of magnitude, if necessary.

[14] Microphone installed in the open field is error-prone because of high winds and other activities around it. To avoid these effects, the microphone and amplifier are housed inside a pit of 30 cm diameter and covered with a sloping hat of 60 cm x 60 cm fixed above four rods of 45 cm height. The hat prevents raindrops from falling directly on the microphone. The sheet used for the hat is stitched with 2 cm thick soft foam to reduce the sound produced by heavy raindrops.

[15] The outputs from all the above sensors are amplified with amplifiers kept near the sensors and fed through coaxial cables to a data logger system which converts and stores the data with a 12 bit analog-to-digital converter. The field mill and the Maxwell current sensor did not show any appreciable zero-shift with time.

3. Storm

[16] A thunderstorm developed 2–4 km northeast of the observatory at ~1530 local time (LT) on 31 May 2002. It moved toward the observatory and covered almost the whole sky over the observatory from 1535 to 1700 LT. Then, its center slowly moved a few kilometers south of the observatory but recurved again toward the observatory in its dissipation stage.

[17] The thunderstorm lasted for ~90 min and gave a very light shower between 1546 and 1550 LT during its initial/mature stage. Rain accompanied with hail of ~1 cm diameter was observed between 1647 and 1705 LT in its dissipating stage. Hail was observed to fall from 1647 to 1651 LT and again from 1700 to 1702 LT. Cloud base during this period was dark and at about 1.5 km above ground level. The occurrence of hail confirmed that the cloud top definitely extended above freezing level which is normally at a height of about 5–6 km in this region. Radiosonde flights made at Mumbai and Aurangabad (two nearest but at ~100 and ~150 km distance respectively, from Pune) show freezing levels at 5.1 and 5.4 km height respectively, on this day. Surprisingly, the observatory also experienced some sunshine during the first incidence of hail. The sun being at a zenith angle of ~40° at this time, the observation indicates that the observatory was nearly below the corner of the northwest sector of the storm.

[18] A meteorological observatory located ~4 km east of our observatory experienced a drop in surface air temperature from 36.8°C to 26.4°C, increase in relative humidity from 28% to 75% and increase in dew point from 20.5°C to

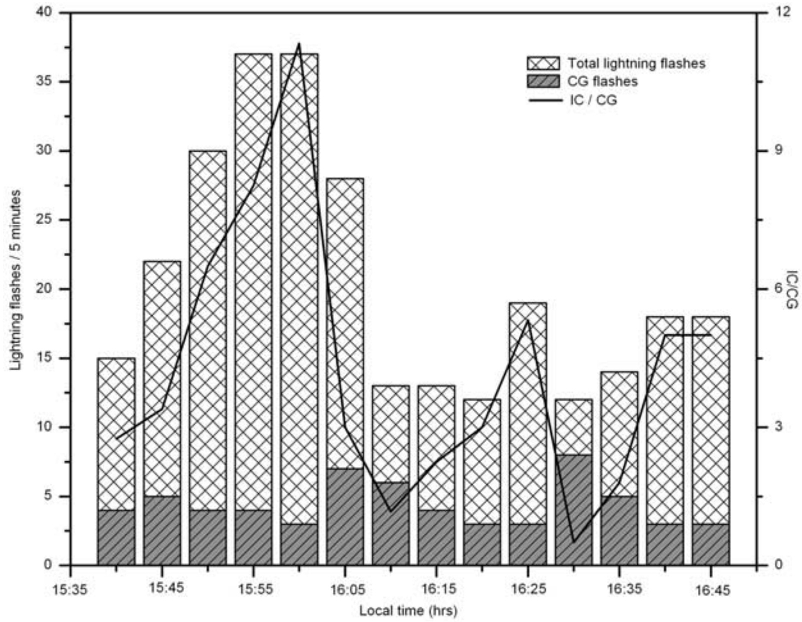

Figure 2. Distribution of 5-min averages of total and CG flashes during lifetime of the hailstorm on 31 May 2002. Solid line shows the variation of IC/CG ratio.

21.9°C from 1500 to 1700 LT. Average surface winds remained below 2 m s^{-1} during this period.

4. Observations

4.1. Intracloud and Cloud-to-Ground Lightning Discharges

[19] The most outstanding feature of this hailstorm was its unusually large number of the CG flashes which were almost uniformly distributed during the storm lifetime. At least 60 CG flashes were visually observed and their approximate times of occurrence noted. Though some flashes could be missed in these observations, it is estimated that more than 90% of CG flashes were recorded since the storm was close to observatory and 2–3 observers simultaneously made visual observations. These CG flashes were spread over almost the whole active life of the storm with an almost constant frequency of one CG flash occurring at an interval of 1 to 2 min. From our observations during last 5–6 years, a typical thunderstorm in this area exhibits even less than 25% of this number of CG flashes in its life time. Moreover, the flash rate is not so uniformly distributed over the period of storm. The storm also exhibited strong activity of IC flashes. Figure 2 shows the numbers of total and CG flashes occurring in every 5 min interval and the variation of IC/CG ratio over almost the full lifetime of the storm. Total flash rate is counted from the electric field records on expanded timescale such as the one shown in Figure 3, a field change of at least 600 V m^{-1} occurring in a period of 2 s being taken as a lightning-induced change. The noise around zero line appeared to be little larger during the period of this storm. However, since it was periodic in nature, it did not interfere with our analysis. Magnitude of field change was chosen following the criterion adopted by *Livingston and Krider* [1978] for overhead thunderstorms. The time period of 2 s was chosen so that even field changes due to multiple discharges, are included. The whole data was examined on expanded timescale. Some field changes such as the one at 1537:30 LT in Figure 3, even though >600 V/m but occurring over a time period of >2 s were not taken as the lightning-induced field changes. Many of such field changes, however, can produce large displacement currents and produce a spike in the Maxwell current density. The CG flash rate is estimated from the visual observations. Precise timings of their occurrence were confirmed from the observations of overshoot in the Maxwell current records [*Deaver and Krider*, 1991; *Pawar and Kamra*, 2004]. After the discharge, value of the Maxwell current density recovers and exceeds the predischarge value by >1 nA m^{-2} in case of CG discharges. Two examples of overshoot following CG discharges are marked in Figures 3 and 4. The total (IC + CG) flash rate sharply increases in the first 20–25 min of the growth of the storm and attains a maximum of ~11 flashes/min at 1555 LT. The rate decreases to about 2 flashes/min at 1615–1620 LT but picks up again and remains at almost constant level of 3–4 flashes/min at 1625–1645 LT. The CG flash activity maintains an approximately constant rate of 0.5–1 flash/min throughout the active life of the storm. Similar rates for CG flashes but with much higher total flash rate have been reported by *Lang et al.* [2000] and *Soula et al.* [2004] in convective storms when hail was present in them. The present storm is comparatively a weaker and short-lived storm with much lower flash rates. In contrast with two storms of *Lang et al.* [2000], this storm is a typical air mass storm that managed to produce some hail. A similar trend is found in Darwin storms by *Rutledge et al.* [1992] and in a deep thunderstorm in France by *Cheze ad Sauvageot* [1997] (as plotted by *Williams* [1985]). Since the CG flash rate in our storm is nearly constant, the IC/CG ratio is just the IC flash rate multiplied by a constant (one flash every 1 to 2 min), So the IC/CG ratio is exactly correlated with the total flash rate (Figure 2) with a correlation coefficient of 0.99.

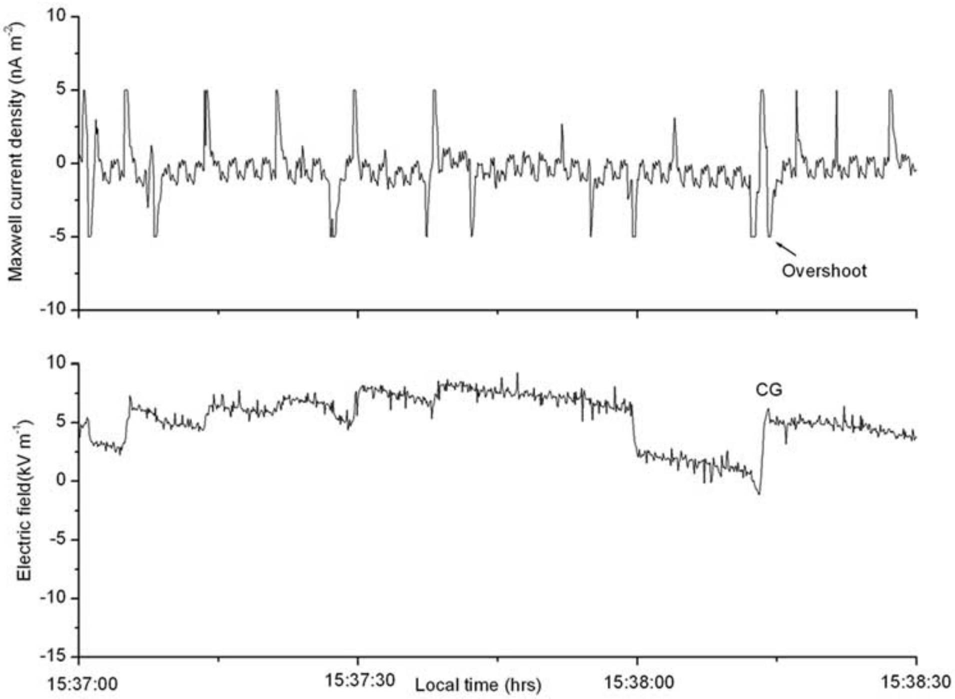

Figure 3. Surface electric field and Maxwell current density record on expanded timescale, showing the two flash pairs and an overshoot.

[20] Figure 5 illustrates the distance of the flashes calculated from the time-to-thunder technique. The different stages of the storm, marked in Figure 5 and the characteristics of flash distribution in these stages are discussed in the next section. The plot in Figure 5 shows positions of only ~48% of the total number of flashes as it was not always possible to exactly identify the acoustic signal corresponding to each and every flash, especially when the flash rate was high. The time of arrival of the first thunder was used in our calculations to calculate the distance of lightning flash. Any horizontal extension of the flash, as most of them are known to have, is thus another source of uncertainty in our calculations of the distance of the flash. Overall distribution of the plotted flashes, however, confirms that the distance of CGs never exceeded ~5 km from the observatory. Further, Figure 5 also supports our visual observations that the storm moved toward the observatory in its initial stage and its centre was almost overhead from 1540 to 1605, moved away from the observatory until ~1630 and then recurved again toward the observatory in its final stages.

[21] The polarity of a CG flash for plotting in Figure 5 is determined by the polarity of the associated surface field change. This method has two factors of uncertainty. First, as pointed out by *Jacobson and Krider* [1976], there are problems in interpreting the polarity of surface field changes caused by CG flashes at close range because sometimes they are dominated by the LPCC. For example, the surface electric field may still be dominated by the LPCC, even if the CG flash is negative. Secondly, multiple-stroke + CG flashes are rare and in all documented cases, each stroke has a different ground contact point. Surface field changes do not provide any information regarding the ground contact point. There may be ambiguity in identifying corresponding electric field and thunder signals. Plots of positive and

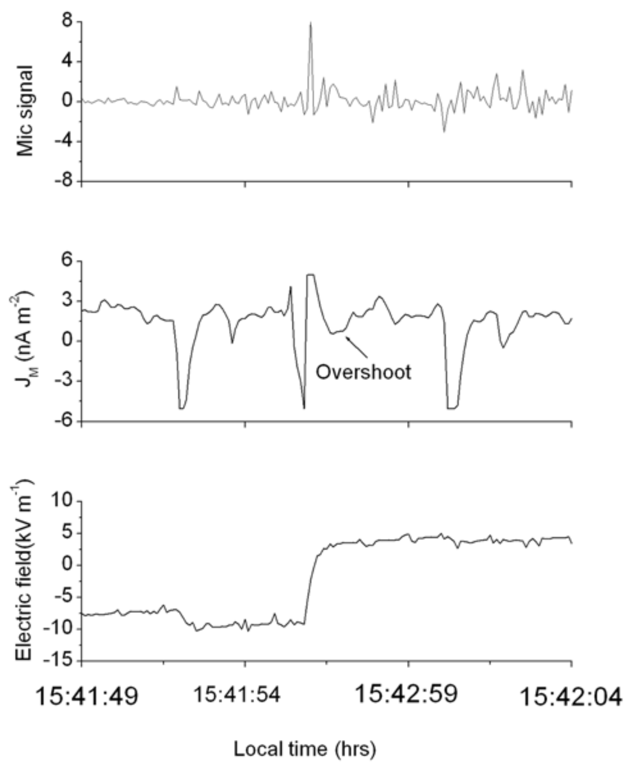

Figure 4. Surface electric field, Maxwell current density (J_M) and microphone records on expanded timescale around the CG flash at 1541 LT.

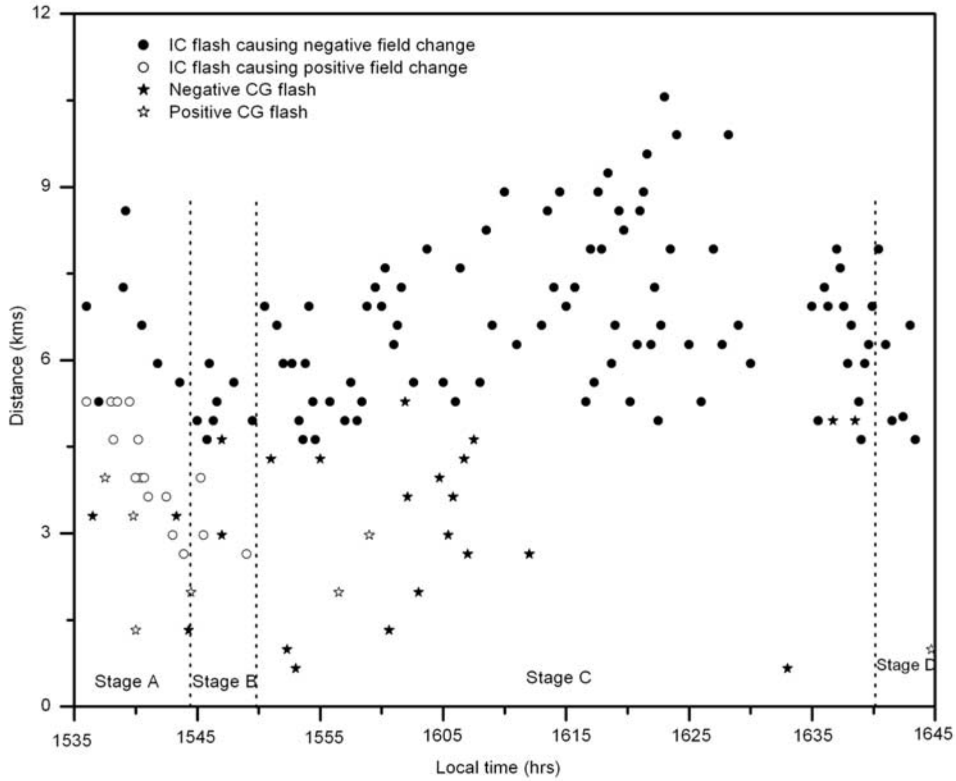

Figure 5. Distances of the different types of flashes calculated from the time-to-thunder technique in different stages of the storm.

negative CG flashes in Figure 5, therefore, need be interpreted in view of these uncertainties.

4.2. Evolution of Storm Electrification

[22] Figure 5 shows the surface electric field and the Maxwell current record made over almost the entire active period of the hailstorm. Records of acoustic signals simultaneously made with a microphone are not shown in Figure 6 to avoid the crowding. Although formation of the cloud was visually observed from its initial stage, observations could not be made in the first 5–10 min for the initial development of the storm and could not be continued for the last 10–15 min during the dissipation stage because of power failure. At the time of the start of observations, the electric field of positive polarity had already grown to a few kilovolts per meter level at 1535 LT and the storm was already exhibiting some lightning activity. On the basis of the electric field and electric field changes records the evolution of electrical activity in the thunderstorm can be divided into the following four different stages, a reference to meteorological state of development in each stage is based only on division of lifetime of a normal thunderstorm of this duration, and visual observations.

4.2.1. Stage A: Convective Stage

[23] In stage A, the thunderstorm has already developed and the negative charge overhead dominates the electric field measured at the ground. The electric field has grown high enough to produce lightning discharges. The gradual and systematic decrease in distances observed for all similar types of flashes in this stage indicates the movement of the storm toward the observatory. In the convective stage of the storm, field changes from consecutive flashes were generally found to alternate in polarity. However, exceptions to this order occur sometimes when two/three consequent field changes are of same polarity. The magnitude of such similar polarity field changes is comparatively much smaller indicating that either the flash is too far or too weak. For example, in Figure 7, we have marked all negative field changes with odd numbers and all positive field changes with even numbers. Consecutive field changes of similar polarity are marked with the same number followed by a letter of the alphabet. Numbers in brackets give the distance of flashes from the observatory. In deciding in respect of a field change, however, it need be pointed out that all field changes do not fulfill the criteria of being a lightning-induced field change as described in section 4.1. The field changes are marked in Figure 7, accordingly. The number of flashes in Figures 2 and 7 may not exactly tally with each other because the averaging periods used in Figure 7 may not exactly correspond to stage A in Figure 2. An important feature of these field changes is that these flashes, most of the time, occur in pairs in which the second flash of the pair produces an electric field change opposite to that of the first and the two flashes of pair are separated with a time difference of 2–20 s. Keeping in view various complexities of the different phenomenon involved in determining the tendencies described above, our results provide good statistical trends. The electric field following the first flash of such pairs does not generally recover to its predischarge value. Instead, it either remains constant or even increases to larger magnitudes. We will further discuss the characteristics of these pairs of field changes in section 5. Moreover,

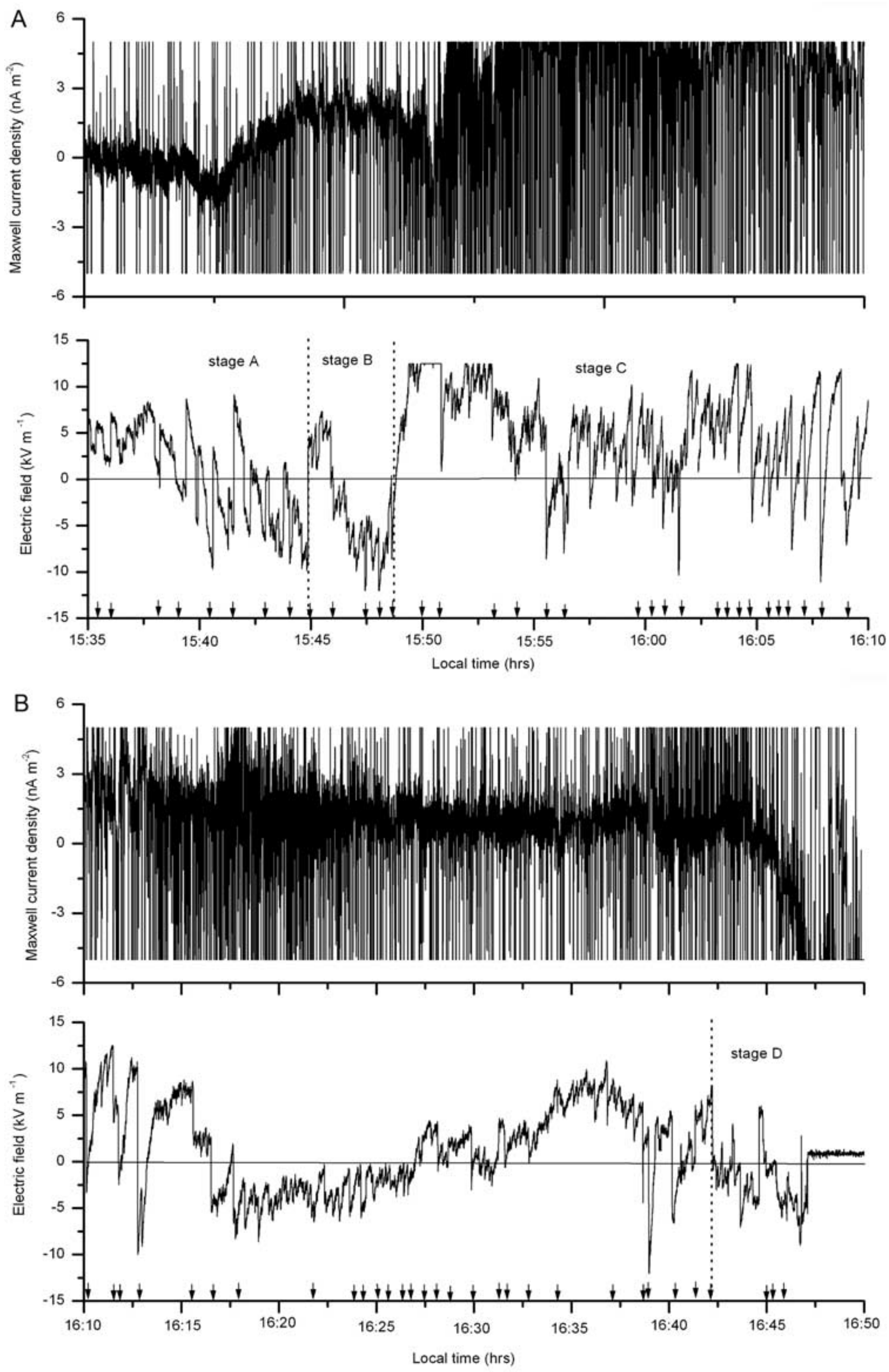

Figure 6. Time variations of surface electric field and the Maxwell current density during cumulus, mature and dissipating stages of the hailstorm. The fair-weather polarity of electric field is plotted as negative. Arrows on time axis of the electric field record indicate timings of CG flashes.

irrespective of the lightning induced electric field changes, the tendency of the ambient electric field, throughout this period, is to become more and more negative. During this period, the Maxwell current, though initially small in magnitude, is most of the time of opposite polarity to that of the electric field.

4.2.2. Stage B: A Case of Rain Gush and the FEAWP?

[24] Although our limited measurements are not enough to establish the cause-and-effect relationship, observations

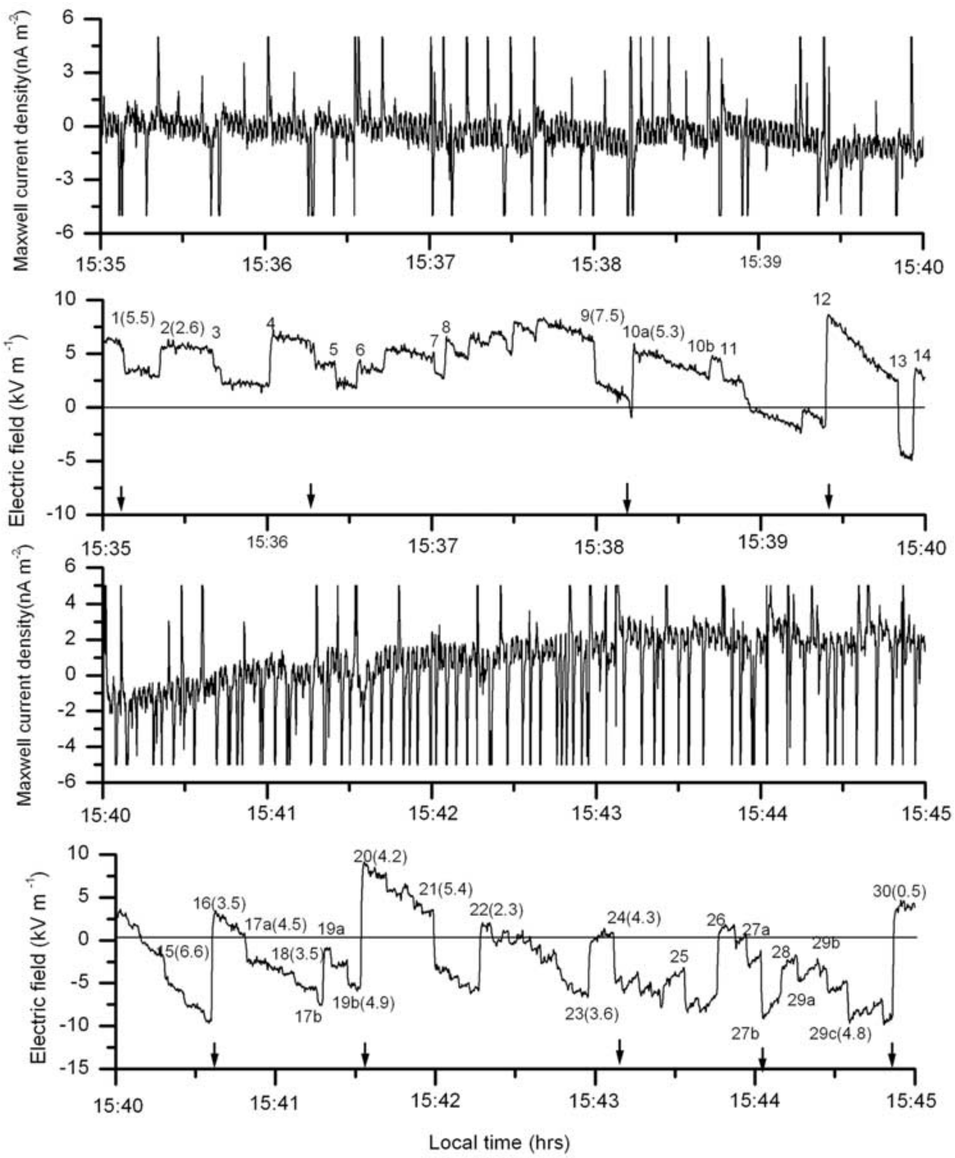

Figure 7. Time variations of electric field and the Maxwell current density on expanded timescale during stage A of the hailstorm. Even and odd numbers show positive and negative field change, respectively. A number followed by a letter shows the field changes of the same polarity. Numbers in brackets show the distance of the flash from the observatory.

made on the ground during stage B follow a sequence of events which suggest the phenomena of the lightning-induced charge transfer, rain gush and the field excursion associated with precipitation (FEAWP) [*Moore and Vonnegut*, 1977; *Szymanski et al.*, 1980; *Vonnegut*, 1983]. The lightning flash occurring at 1541 LT in Figure 6 causes a positive field change of 14 kV m^{-1} which is much larger than most of the other discharges occurring during this period. Both the visual observation and the magnitude of the Maxwell current overshoot accompanying it, confirm it to be a CG flash consisting of more than one stroke. Moreover, this flash struck the ground, as estimated from the time-to-thunder technique, only 400–600 m away from the observatory. The electric field which changes polarity from negative to positive does not show, as shown in Figure 4, any recovery and varies around its after-discharge value. A shower, consisting of relatively large raindrops is observed on the ground between 1546 and 1549. No widespread rain or any shower continuing over longer periods were observed around that time. During this period, the electric field undergoes a negative excursion but soon attains its positive polarity. Following the flash at 1541 LT all discharges in stage B except the two show negative field changes (Figure 6).

[25] The enhanced growth of drops as a result of the deposition of charge by lightning has been proposed by *Moore et al.* [1964] and *Vonnegut* [1983] as a cause of gush of rain at ground. Radar observations of *Szymanski et al.* [1980] confirm that development of radar echo occurs only after the occurrence of discharge. The time period of 1 to 4 min observed between the occurrence of overhead lightning discharge and the raingush at ground is enough for

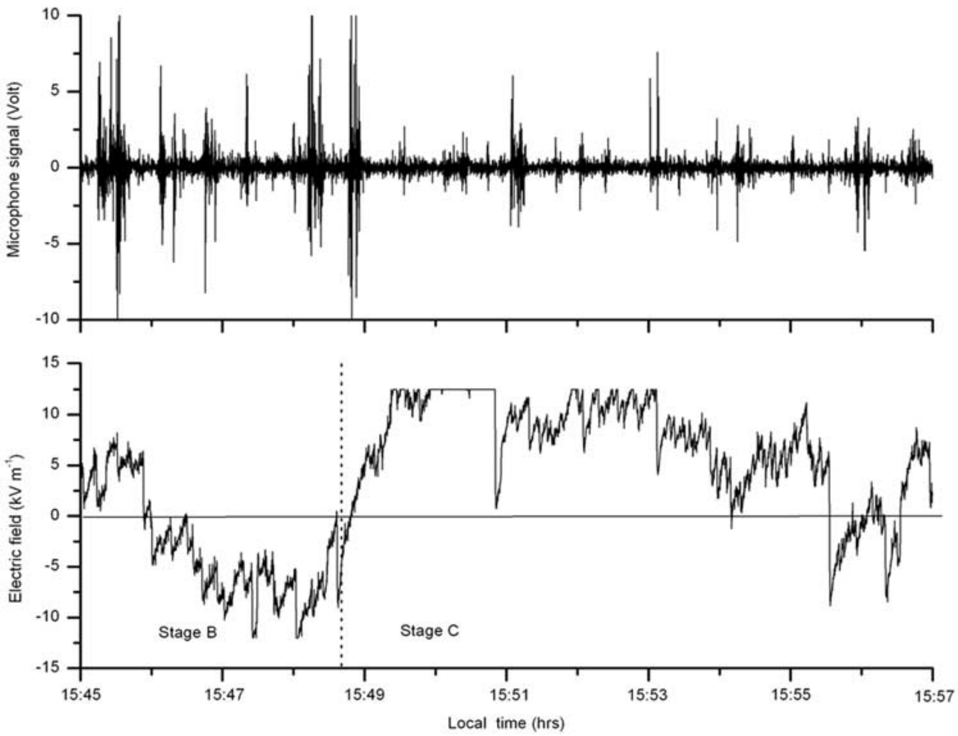

Figure 8. Records of electric field and thunder before and after the transition from stage B to C. Note the weakening of thunder signals for the flashes occurring after the transition and the rapid reversal and strengthening of electric field after the transition.

raindrops of diameters greater than ~3 mm (taking their fall speeds between 8 m s^{-1} (at ground) and 12 m s^{-1} (at 500 hPa level) following *Beard* [1976] to fall an average distance of 0.5–1.5 km from cloud base to ground. The sequence of events in our surface observations is in accordance with such explanation. However, in absence of radar and lightning mapping observations in our experiment, other possibilities such as the CG flash being associated with descending charged precipitation, as discussed by *Carey and Rutledge* [1996], or it being just a coincidence that lightning was associated with falling rain or the falling rain originated away from the charged regions associated with lightning, cannot be ruled out. It is worth noting that after the occurrence of flash at 1541 LT, the charge distribution in the storm changes such that the sequence of subsequent field changes with opposite polarity and occurrence of flash pairs observed in stage A, disappear. Out of 20 discharges that occur in stage B, 18 produce negative field changes.

4.2.3. Stage C: Mature Stage

[26] Stage C in this storm, lasts for ~53 min (Figure 6). It is well distinguished from stage B when the negative electric field of ~10 kV m^{-1} rapidly changes at ~1549 LT in Figure 6 to a positive electric field of more than 12.5 kV m^{-1} in less than a minute. This rapid transition to very large positive values of electric field and Maxwell current indicates the start of a very active period of strong electrification in the initial period of this stage. Any effect of the lower positive charge center (LPCC) on the surface electric field becomes small as compared to that of the overhead negative charge. Observations of comparatively large number of CG flashes occurring in the first 15–20 min of this stage (e.g., see two bars at 1555 and 1600 in Figure 2) suggests the presence of the LPCC [e.g., *Clarence and Malan*, 1957; *Williams*, 1989; *Mansell et al.*, 2002]. Most of these CGs exhibit two or more return strokes. However, all of them cause negative field changes. The sharp increase in total flash rate which peaks at 11 flashes/min at 1555 LT during this period also supports the start of an active period of electrification. Further, contrary to that in stage A, most of the flashes (>98%) occurring during stage C cause negative field changes showing the neutralization of negative charge overhead, irrespective of the polarity of the prevailing surface electric field. Moreover, the increase in flash rate is mostly due to the increase in the rate of intracloud flashes that occur, as supported by Figure 5, in the upper regions of the storm. As pointed out earlier, Figure 5 plots only 48% of the total number of flashes. Large number of flashes, especially those occurring between 1550 and 1600 LT could not be analyzed for plotting in Figure 5 because the large frequency of their occurrence posed ambiguity in identification of the corresponding electric and thunder signals of a flash. Therefore Figure 5 can be used as indicative of the shift in the region of flash activity. Figure 2, however, provides better illustration of the change in frequency of flashes with time. *Williams et al.* [1989] also report that intracloud lightning in thunderstorms is associated with vigorous updrafts. Another feature of lightning flashes that sharply differentiates stage C from stage B, is the weakening of acoustic signal associated with IC flashes occurring in the first ~10 min of stage C (Figure 8). Estimates of the distance computed with the time-to-thunder technique, shown in Figure 5, indicate that most of the IC discharges in stage B occur within 2 to 6 km of the observatory and this

Table 1. Comparison of Time Intervals Between Two Flashes of a Pair and the Consecutive Pairs

Serial Number	Flash Pair	Time Interval Between Two Flashes of a Pair, s	Time Interval Between Consecutive Pairs,[a] s
1	1–2	12.9	22.1
2	3–4	19.1	23.1
3	5–6	17.8	28.1
4	7–8	4.0	54.6
5	9–10	38.0	32.0
6	11–12	6.3	22.0
7	13–14	18.0	27.0
8	15–16	4.0	38.9
9	17–18	13.4	26.0
10	19–20	17.0	27.0
11	21–22	10.0	40.0
12	23–24	12.0	26.0
13	25–26	8.0	17.0
14	27–28	20.0	25.0
Average		14.3 ± 8.4	29.3 ± 9.1

[a]Interval is between the II flash of a flash pair given in the second column and the I flash of the flash pair immediately following it.

distance increases to 4.5 to 10 km in stage C. These observations coupled with the fact that the distance of CG flashes does not undergo much change in the two stages, suggest that the region where most of the IC flashes occur in stage B is lifted up in stage C [*Rutledge et al.*, 1992; *MacGorman et al.*, 1989]. These observations imply the presence of a strong updraft and rapid vertical growth of the storm. The association of increase in thunderstorm size and electrical activity with the prevalence of IC and IC/CG ratio has also been observed in a Florida storm by *Williams* [1985] and in Australian storms by *Rutledge et al.* [1992]. Such upward lifting of the region of flash occurrence, however, needs to be confirmed from the observations with Doppler radar and lightning mapping array [*Rust et al.*, 2005].

4.2.4. Stage D: Dissipation Stage

[27] Stage D which lasts from ~1642 LT to the end of the storm, can be associated with the beginning of the dissipating stage of the storm when the condensate and the positive charge residing on it and accumulated in upper parts of the cloud descends and creates low-level downdrafts. The creation of downdrafts is further fueled by the evaporative cooling created by the evaporation of falling drops near to the edges of downdraft. It is marked with a sharp decrease and even change in polarity of both the electric field and the Maxwell current from positive to negative at 1650 LT. It is also marked with at least 4 positive CG flashes (marked by arrows on time axis in Figure 6b). Occurrence of such positive CG flashes in the dissipating stage of the storm has also been reported by *Moore and Vonnegut* [1977], *Marshall and Winn* [1982] and *Mo et al.* [2002]. Hail of ~1 cm diameter accompanied with rain was observed in this stage at ground. Hail fell from 1647 to 1651 and again from 1700 to 1702. Observations of hail at ground in this stage suggests that the descending hail in the storm might fuel the downdraft and thus may add to the dissipation of the storm. Unfortunately, our observations could not be continued beyond 1648 because of power failure. However, the records of thunder which continued even after 1648, showed that the lightning activity almost ceased to occur after the observations of rain and hail in the observatory. An examination of the data during dissipation stage showed that most of the flashes recorded in this stage occurred within 6 km of the observatory (Figure 5).

5. Lightning-Induced Charge Transfer and Triggering of Lightning

[28] Stage A provides an excellent and unique period in which the flash pairs, as discussed in section 4.2.1 occur repeatedly. To strengthen our claim of observing flash pairs in stage A, Table 1 shows a comparison of the time interval between the first and second flashes of a pair and the time interval between that pair and the next consecutive pair. In cases where 2–3 consecutive flashes are of same polarity, the time lapsed between two flashes of a pair is counted as the time period between the last similar polarity flash and flash of opposite polarity. The average time interval between the two flashes of a pair is only 14.3 ± 8.4 s as against an average time period of 29.3 ± 9.1 s which elapses between the occurrence of two consecutive pairs. The two flashes in a pair may be separated by 4–20 s in time and by a few kilometers in space. The first of these field changes in every pair in stage A is always of negative polarity (except the one pair consisting of flash numbers 23 and 24 in Figure 7) indicating neutralization of negative charge overhead followed by a second one of positive polarity showing neutralization of positive charge overhead. Moreover, as illustrated in Table 2, the distance of the flashes causing negative field change is always greater than those of the flashes causing a positive field change. The average distances of the flashes causing negative and positive field changes in this stage are 6.2 ± 0.91 and 4.1 ± 0.95 km, respectively (Table 2). The similar difference in distances was observed in some cases for the flashes of the same pair. It was not always possible to identify the electric field change and acoustic signals corresponding to both flashes of a pair. However, it was possible to do it in a few cases. Numbers in brackets written for some flashes in Figure 7

Table 2. Average Distance of Lightning Flashes Derived From the Time-to-Thunder Technique in Different Stages of the Storm[a]

Stage	IC Flashes Causing Negative Field Change	IC Flashes Causing Positive Field Change	Negative CG	Positive CG
A	6.2 ± 0.91	4.1 ± 0.95	2.3 ± 1.4	2.1 ± 1.6
B	5.06 ± 0.5	2.64 ± 0.5	3.79 ± 0.85	–
C	6.7 ± 1	–	3.5 ± 1.9	2.4 ± 0.7
D	5.4 ± 0.6	–	–	0.99

[a]Unit is km.

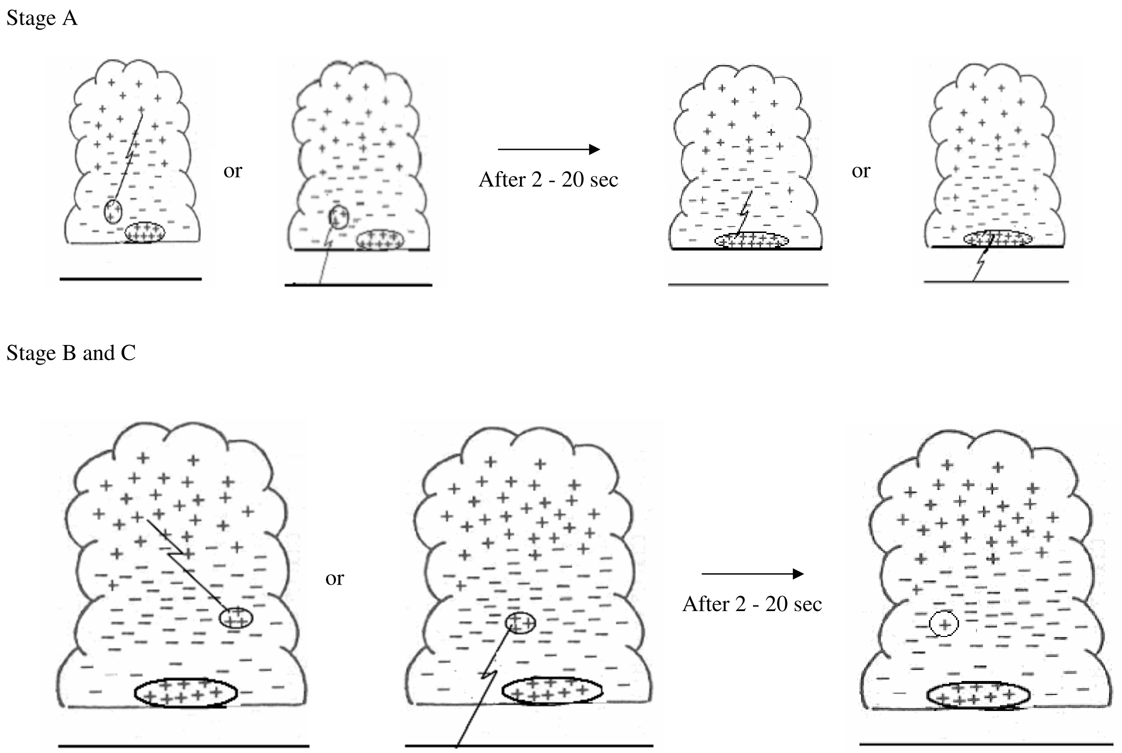

Figure 9. A schematic diagram to explain the frequent occurrence of pairs of the lightning-induced field changes in stage A as compared to other stages of the thundercloud.

depict the distances of the flashes and illustrate the difference in distances of the flashes of opposite polarity of the same pair. One way to explain this observation may be that the flashes causing negative field change occur in higher regions and this eventually triggers a discharge in the lower regions of the storm. Polarity-wise, this rule holds good even in case of anomalous pair consisting of flashes 23 and 24. As many as 13 pairs of field changes are observed within a time span of 10 min. Many of these flash pairs were visually observed as CG flashes, i.e., a −CG flash followed by a +CG flash coming down from the cloud separated by rather short time but up to a few kilometers in distance. In such cases, however, the difference in distance cannot be due to the height of the neutralized charges. The field changes caused by the two flashes in a pair may be equal or grossly different from each other. However, the electric field after the second flash and during the period between the two flashes continued to build up at the same rate as before the first discharge but at a different level.

[29] Time frame of the triggering of lightning described above is much different from that described earlier by *Pawar and Kamra* [2004]. In the later case, the triggered discharge followed immediately after the first flash suggesting that both discharges involved at least one common charge volume. In the present case, the triggered discharge is delayed by 4–20 s and the two discharges, as observed sometimes, may be widely separated in space. Rearrangement of the charge transported in the first discharge and build up of new charges during the time period between the two lightning discharges may significantly change the electrical structure of the cloud. This modified electrical structure may enhance the electric stress and result in breakdown to trigger the second discharge in some other region of the cloud.

[30] Occurrence of such flash pairs is not so commonly observed in other stages. For example, stages B, C and D each exhibit only two such pairs. Regions of occurrence of the opposite polarity flashes in a flash pair and the reasons for rarely or even not observing such pairs in other stages of the storm can be speculated from our observations. The speculated mechanism is illustrated in a schematic diagram in Figure 9. In the initial stages, the cloud is shallow and its depth as well as area of the LPCC are expanding. Within the tripole structure of the storm, the first flash of a pair is either an IC flash in the main positive dipole or a −CG flash from the negative charge center of the storm. Either of these can deposit a positive charge in the negative charge region of the storm [*Holden et al.*, 1983; *Marshall and Winn*, 1982; *Mo et al.*, 2002; *Coleman et al.*, 2003; *Warner et al.*, 2003; *Rust et al.*, 2005]. Since the cloud is comparatively shallow in this initial stage of the growing cloud, the regions of flash-deposited positive charge is relatively close to the expanding LPCC and, by neutralizing the intervening negative charge layer during the interdischarge period, can shift and merge with it. Their merger will enhance the electrical stress between the LPCC and the negative charge center and/or the ground and may trigger the second discharge: either an IC flash between the LPCC and negative charge centre or a CG flash between the LPCC and the ground. In the later stages when the storm has grown, both vertically and horizontally in size, the regions

of flash-deposited charge and the LPCC may be too far to merge with each other in the interdischarge period.

6. Discussion

[31] Our results of the increase in IC/CG ratio with total flash rate observed in storms of moderate lightning activity are consistent with the earlier results of *Rutledge et al.* [1992] obtained during The Down Under Doppler and Electricity Experiment (DUNDEE) conducted near Darwin and those of *Cheze and Sauvageot* [1997] in storms over Australia (as plotted by *Williams* [2001]). Large values of IC/CG ratio have also been reported by *Goodman et al.* [1988] and *MacGorman et al.* [1989] in extraordinary electrically active tornadic storms in the middle latitudes. *Rutledge et al.* [1992] interpreted the higher IC/CG ratios as a higher probability of intracloud flashes as the altitude of the charge separation process and region of high electric field rises to higher altitudes where the dielectric strength of the atmosphere is weaker. Higher values of IC/CG ratio (Figure 2) observed in matured stage of this hailstorm support this conclusion. The narrow nature of the clouds relative to their heights in the tropics has also been suggested to explain the infrequent occurrence of ground flashes of such severe storms in such regions [*Williams*, 2001]. On the contrary laterally extensive charge regions in midlatitudes, are more likely to provide the electrostatic energy required to bridge the long gap to ground.

[32] In early measurements of the electrical moment destroyed in a lightning flash, an intracloud (IC) flash is generally considered to neutralize equal and opposite charges in a thundercloud [*Uman*, 1969]. However, *Moore et al.* [1964] has proposed that a flash, instead of neutralizing the involved charges, may transfer and redistribute them in the lightning channels so as to reduce the electrical stress. In modeling studies of horizontally extended system, *Marshall and Stolzenburg* [2002] reported that equal and opposite charges need not be neutralized to maximize the reduction in electrical stress. Our observations, especially in stage A of this storm of much smaller horizontal extent also suggest that redistribution of charges after a flash may modify the electric field in some other regions of the thunderstorm, sometimes at remote distances from the flash, so as to trigger another flash there. The fact that such flash pairs have been frequently observed in stage A and only rarely in stage C (only two pairs in a time period of 53 min) implies that the initial conditions of small vertical depth and simple electrical structure of thunderstorms are favorable for such triggering of second discharge. Moreover, the tendency in the growth of the large-scale ambient electric field before the first flash, between the two flashes of a pair, and after the second flash, in case of each flash, pair, remains same. It is worth noting that only exception to this tendency of the field change similarity is the abnormal pair involving flashes 23 and 24 where the first flash in a pair produces a positive field change and the second flash produces a negative field change.

[33] The rapid increase in electric field and the Maxwell current that marks the start of stage C is accompanied with sharp rise in the flash rate. In a period of ~52 min that this stage lasts, all but two flashes produce negative field changes and produce comparatively weaker thunder signals (Figure 8). Spread of CG flashes over a distance of 4–5 km in Figure 5 shows the horizontal extension of the storm over the observatory. Since the storm did not show much horizontal movement during this time, the increasing distances of flashes in Figure 5 suggest the elevation of the charge center to higher altitudes by strong updrafts as suggested by *MacGorman et al.* [1989].

[34] Falling of hail and rain at ground in the dissipating stage of the storm suggests the collapse of the cloud top and lowering of positive charge from the upper portions of the storm with the downdrafts as proposed by *Moore and Vonnegut* [1977] to explain the EOSO. Change of the electric field from positive to negative polarity and the sharp change of the Maxwell current in our observations support such a charge transport. Since the EOSO is often associated with the formation of a radar bright band, the aggregating and falling of ice crystals carrying positive charge from the upper regions of the storm may also contribute to its occurrence [*Williams and Boccippio*, 1993]. Full illustration of the EOSO in our observations might have been missed because observations could not be continued in the last 10–15 min of the storm period because of the power failure.

7. Conclusions

[35] A total of more than 60 CG flashes occurring at an approximately constant rate of one flash every 1 or 2 min spread over almost whole active life of a tropical air mass hailstorm in premonsoon season are reported. Observations show that the lightning-induced field changes in the surface electric field change their character in different stages of the storm. In cumulus stage, almost every consecutive field change is of opposite polarity. Moreover, field changes in this stage occur in pairs, the first one being of negative polarity and the second one of positive polarity. The two field changes are separated by 2–20 s in time and the flashes causing them can be IC or CG that can be separated in space by even a few kilometers. The distances of flashes calculated from the time-to-thunder technique indicate that the first flash of the pair occurs in the upper regions and the second one in the lower regions of the storm. In mature stage total flash rate reaches a peak of 11 flashes/min and mostly all flashes cause negative field changes. In the dissipating stage, the storm exhibits 4 +CG flashes.

[36] The fact that the CG flash rate is nearly constant and the IC/CG ratio is strongly correlated with the total flash rate implies that the use of the CG flash rate as a proxy of convective intensity is not justified. Our observations also suggest that the charge transferred in some flashes can change the charge distribution in the storm in such a way that it can trigger another flash.

References

Banerjee, S. K. (1930), The electric field of overhead thunderclouds, *Q. J. R. Meteorol. Soc.*, *56*, 305–334.

Banerjee, S. K. (1932), The electric field of overhead thunderstorms, *Philos. Trans. R. Soc., Ser. A*, *231*, 1–27.

Bateman, M. G., T. C. Marshall, M. Stolzenburg, and W. D. Rust (1999), Precipitation charge and size measurements inside a New Mexico mountain thunderstorm, *J. Geophys. Res.*, *104*, 9643–9653.

Beard, K. V. (1976), Terminal velocity and shape of cloud and precipitation drops aloft, *J. Atmos. Sci.*, *33*, 851–864.

Carey, L. D., and S. A. Rutledge (1996), A multiparameter radar case study of the microphysical and kinematic evolution of a lightning producing storm, *Meteorol. Atmos. Phys.*, *59*, 33–64.

Cheze, J. L., and H. Sauvageot (1997), Area-average rainfall and lightning activity, *J. Geophys. Res.*, *102*, 1707–1716.

Clarence, N. D., and D. J. Malan (1957), Preliminary discharge processes in lightning flashes to ground, *Q. J. R. Meterol. Soc.*, *83*, 161–172.

Coleman, L. M., T. C. Marshall, M. Stolzenburg, T. Hamlin, P. R. Krehbiel, W. Rison, and R. J. Thomas (2003), Effects of charge and electrostatic potential on lightning propagation, *J. Geophys. Res.*, *108*(D9), 4298, doi:10.1029/2002JD002718.

Deaver, L. E., and E. P. Krider (1991), Electric fields and current densities under small Florida thunderstorms, *J. Geophys. Res.*, *96*, 2273–2281.

Goodman, S. J., D. E. Buechler, P. D. Wright, and W. D. Rust (1988), Lightning and precipitation history of a microburst-producing storm, *Geophys. Res. Lett.*, *15*, 1185–1188.

Holden, D. N., C. R. Holmes, C. B. Moore, W. P. Winn, J. W. Cobb, J. E. Griswold, and D. M. Lytle (1983), Local charge concentrations in thunderclouds, in *Proceedings in Atmospheric Electricity*, edited by L. H. Rhunke and J. Latham, pp. 179–183, A. Deepak, Hampton, Va.

Illingworth, A. J. (1985), Charge separation in thunderstorms: Small scale processes, *J. Geophys. Res.*, *90*, 6026–6032.

Jacobson, E. A., and E. P. Krider (1976), Electrostatic field changes produced by Florida lightning, *J. Atmos. Sci.*, *33*, 103–117.

Krehbiel, P. R. (1986), The electrical structure of thunderstorms, in *The Earth's Electrical Environment*, Geophysics Study Committee, pp. 90–113, Natl. Acad. Press., Washington, D. C.

Krider, E. P., and R. J. Blakeslee (1985), The electric currents produced by thunderclouds, *J. Electrost.*, *16*, 369–378.

Krider, E. P., and J. A. Musser (1982), Maxwell currents under thunderstorm, *J. Geophys. Res.*, *87*, 11,171–11,176.

Lang, T. J., S. A. Rutledge, J. E. Dye, M. Venticinque, P. Laroche, and E. Defer (2000), Anomalously low negative cloud-to-ground lightning flash rates in intense convective storms observed during STERAO-A, *Mon. Weather Rev.*, *128*, 160–173.

Latham, J. (1981), The electrification of thunderstorms, *Q. J. R. Meteorol. Soc.*, *107*, 277–298.

Livingston, J. M., and E. P. Krider (1978), Electric fields produced by Florida thunderstorms, *J. Geophys. Res.*, *83*, 385–401.

MacCready, P. B., and A. Proudfit (1965), Observations of hydrometeor charge evolution in thunderstorms, *Q. J. R. Meteorol. Soc.*, *91*, 44–53.

MacGorman, D. R., V. Mazur, W. D. Rust, W. L. Taylor, and B. C. Johnson (1989), Lightning rates relative to tornadic storm evolution on 22 May, 1981, *J. Atmos. Sci.*, *46*, 221–250.

Mansell, E. R., D. R. MacGorman, C. L. Ziegler, and J. M. Straka (2002), Simulated three-dimensional branched lightning in a numerical thunderstorm model, *J. Geophys. Res.*, *107*(D9), 4075, doi:10.1029/2000JD000244.

Mansell, E. R., D. R. MacGorman, C. L. Ziegler, and J. M. Straka (2005), Charge structure and lightning sensitivity in a simulated multicell thunderstorm, *J. Geophys. Res.*, *110*, D12101, doi:10.1029/2004JD005287.

Marshall, T. C., and W. D. Rust (1991), Electric field soundings through thunderstorms, *J. Geophys. Res.*, *96*, 22,297–22,309.

Marshall, T. C., and M. Stolzenburg (1998), Estimates of cloud charge densities in thunderstorms, *J. Geophys. Res.*, *103*, 19,769–19,775.

Marshall, T. C., and M. Stolzenburg (2002), Electrical energy constraints on lightning, *J. Geophys. Res.*, *107*(D7), 4052, doi:10.1029/2000JD000024.

Marshall, T. C., and W. P. Winn (1982), Measurements of charged precipitation in a New Mexico thunderstorm: Lower positive charge centers, *J. Geophys. Res.*, *87*, 7141–7157.

Mo, Q., J. H. Helsdon Jr., and W. P. Winn (2002), Aircraft observations of the creation of lower positive charges in thunderstorms, *J. Geophys. Res.*, *107*(D22), 4616, doi:10.1029/2002JD002099.

Moore, C. B., and B. Vonnegut (1977), The thundercloud, in *Lightning*, vol. 1, edited by R. H. Golde, pp. 51–98, Elsevier, New York.

Moore, C. B., B. Vonnegut, E. A. Vrablik, and D. A. McCraig (1964), Gushes of rain and hail after lightning, *J. Atmos. Sci.*, *21*, 646–665.

Murphy, M. J., E. P. Krider, and M. W. Maier (1996), Lightning charge analysis in small convective and precipitation electrification (CAPE) experiment storms, *J. Geophys. Res.*, *101*, 29,615–29,625.

Pawar, S. D., and A. K. Kamra (2002), Recovery curves of the surface electric field after lightning discharges occurring between the positive charge pocket and negative charge centre in a thundercloud, *Geophys. Res. Lett.*, *29*(23), 2108, doi:10.1029/2002GL015675.

Pawar, S. D., and A. K. Kamra (2004), Evolution of lightning and the possible initiation/triggering of lightning discharges by the lower positive charge center in an isolated thundercloud in the tropics, *J. Geophys. Res.*, *109*, D02205, doi:10.1029/2003JD003735.

Reynolds, S. E., M. Brook, and M. F. Gourley (1957), Thunderstorm charge separation, *J. Meteorol.*, *14*, 426–436.

Rust, W. D., and T. C. Marshall (1996), On abandoning the thunderstorm tripole-charge paradigm, *J. Geophys. Res.*, *101*, 23,499–23,504.

Rust, W. D., D. R. MacGroman, E. C. Bruning, S. A. Weiss, P. R. Krehbiel, R. J. Thomas, W. Rison, T. Hamlin, and J. Harlin (2005), Inverted-polarity electrical structure in thunderstorms in the Sever Thunderstorm Electrification and Pricipitation Study (STEPS), *Atmos. Res.*, *76*, 247–271.

Rutledge, S. A., E. R. Williams, and T. D. Keenan (1992), The Down Under Doppler and Electricity Experiment (DUNDEE): Overview and preliminary results, *Bull. Am. Meteorol. Soc.*, *73*, 3–16.

Saunders, C. P. R. (1995), Thunderstorm electrification, in *Handbook of Atmospheric Electrodynamics*, edited by H. Volland, pp. 61–92, CRC Press, Boca Raton, Fla.

Saunders, C. P. R., W. D. Keith, and R. P. Mitzeva (1991), The effect of liquid water on thunderstorm charging, *J. Geophys. Res.*, *96*, 11,007–11,017.

Simpson, G. C., and G. D. Robinson (1941), The distribution of electricity in thunderclouds, 2, *Proc. R. Soc., Ser. A*, *177*, 281–329.

Simpson, G. C., and F. J. Scrase (1937), The distribution of electricity in thunderclouds, *Proc. R. Soc., Ser, A*, *161*, 309–352.

Soula, S., Y. Seity, L. Feral, and H. Sauvageot (2004), Cloud-to-ground lightning activity in hail-bearing storms, *J. Geophys. Res.*, *109*, D02101, doi:10.1029/2003JD003669.

Stolzenburg, M., W. D. Rust, B. F. Smull, and T. C. Marshall (1998), Electrical structure in thunderstorm convective regions: 1. Mesoscale convective systems, *J. Geophys. Res.*, *103*, 14,059–14,078.

Szymanski, E. W., S. J. Szymanski, C. R. Holmes, and C. B. Moore (1980), An observation of precipitation echo intensification associated with lightning, *J. Geophys. Res.*, *85*, 1951–1953.

Takahashi, T. (1978), Riming electrification as a charge generation mechanism in thunderstorms, *J. Atmos. Sci.*, *35*, 1536–1548.

Uman, M. A. (1969), *Lightning*, Dover, Mineola, N. Y.

Vonnegut, B. (1963), Some facts and speculations concerning the origin and role of thunderstorm electricity, *Meteorol. Monogr.*, *5*, 224–241.

Vonnegut, B. (1983), Deduction concerning accumulation of electrified particles in thundercloud based on electric field changes associated with lightning, *J. Geophys. Res.*, *88*, 3911–3912.

Warner, T. A., J. H. Helsdon Jr., and A. G. Detwiler (2003), Aircraft observations of a lightning channel in STEPS, *Geophys. Res. Lett.*, *30*(19), 1984, doi:10.1029/2003GL017334.

Williams, E. R. (1985), Large scale charge separation in thunderclouds, *J. Geophys. Res.*, *90*, 6013–6025.

Williams, E. R. (1989), The tripole structure of thunderstorms, *J. Geophys. Res.*, *94*, 13,151–13,167.

Williams, E. R. (2001), The electrification of severe storms, *Meteorol. Monogr.*, *28*(50), 527–561.

Williams, E. R., and D. J. Boccippio (1993), Dependence of cloud microphysics and electrification on mesoscale vertical air motion in stratiform precipitation, in *Conference on Atmospheric Electricity*, pp. 825–831, Am. Meteorol. Soc., St. Louis, Mo.

Williams, E. R., M. E. Weber, and R. E. Orville (1989), The relationship between lightning type and convective state of thunderclouds, *J. Geophys. Res.*, *94*, 13,213–13,220.

Williams, E. R., R. Zhang, and J. Rydock (1991), Mixed-phase microphysics and cloud electrification, *J. Geophys. Res.*, *48*, 2195–2203.

Wilson, C. T. R. (1929), Some thundercloud problems, J., *Franklin Inst.*, *208*, 1–12.

A. K. Kamra and S. D. Pawar, Indian Institute of Tropical Meteorology, Pune 411 008, India. (kamra@tropmet.res.in)